BALLISTIC TRANSPARENT ARMOR TESTING
USING A MULTI-HIT RIFLE PATTERN

A thesis written at

U.S. ARMY TANK-AUTOMOTIVE COMMAND

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in partial fulfillment
of the requirements for the
degree of

BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING

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DISCLAIMER

This thesis is submitted as partial and final fulfillment of the cooperative work experience requirements of Kettering University needed to obtain a Bachelor of Science in Mechanical Engineering.

The conclusions and opinions expressed in this thesis are those of the writer and do not necessarily represent the position of Kettering University or U.S. Army Tank-Automotive Command, or any of its directors, officers, agents, or employees with respect to the matters discussed.

PREFACE

This thesis represents the capstone of my five years combined academic work at

Kettering University and job experience at U.S. Army Tank-Automotive Command.

Academic experience in statistics, material science, and mechanical engineering proved

to be valuable assets while I developed this thesis and addressed the problem it concerns.

Although this thesis represents the compilation of my own efforts, I would like to

acknowledge and extend my sincere gratitude to the following persons for their valuable

time and assistance, without whom the completion of this thesis would not have been

possible:

1. My parents, family, and friends, who really had nothing to do with this thesis, but have had EVERYTHING to do with every other thing in my life. I love you all.

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I. INTRODUCTION

Problem Topic

Currently, the United States Army does not have a ballistic standard for measuring the multi-hit performance of its transparent armor (TA). The results of this testing may aid in the establishment of a ballistic performance standard. A draft TACOM Transparent Armor Purchase Document (ATPD 2352) has been written based on early testing. This study adds data to validate the outlined ballistic testing method and conformance of the TA to the light transmission requirements. This information is pertinent to the development of new solutions (e.g. recipes of glass laminations) that may further improve the protection of occupants of U.S. Army vehicles.

Background

Since the beginning of Operation Iraqi Freedom (Iraq) and Operation Enduring Freedom (Afghanistan) occupant safety in U.S. Army vehicles has become an escalating issue. U.S. Army vehicles in operation are facing increased threats from armed insurgents and improvised explosive devices (IEDs). As a result, the U.S. Army is constantly evaluating its vehicles, looking for ways to improve their protection capabilities. The windows and windshield, usually the most targeted areas of the vehicle, are given extra attention.

Most transparent armor solutions consist of layers made from glass and plastic. The number of layers in each solution and their respective thicknesses can be varied to achieve different ballistic protection capabilities. Bullet projectiles typically behave differently than fragments from an IED, therefore specific solutions can be made to better protect against one threat or the other.   Figure 1 is an edge view of sample transparent armor and details each of the layers as they appear in the solution.
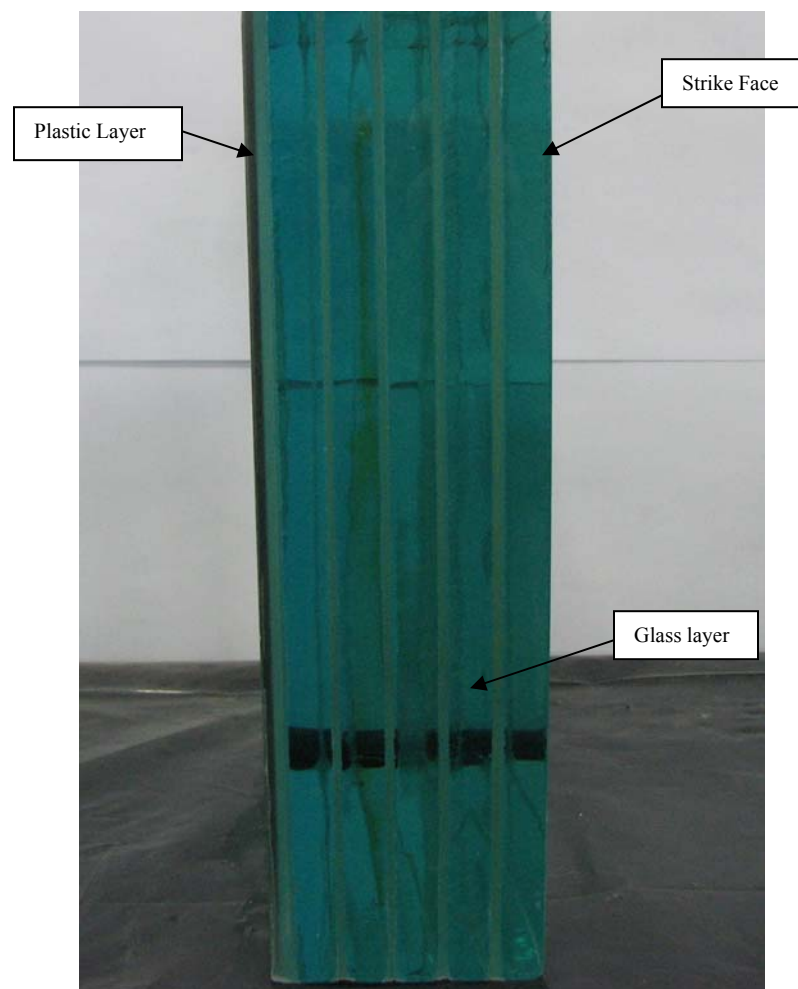

Figure 1. Transparent armor – edge view.

When a solution is installed on a vehicle, the surface that the projectile first impacts is called the strike face. The strike face is made of glass so that the solution can initially absorb large amounts of energy. Also the glass provides scratch and abrasion resistance which may occur from windshield wipers, or from dusty, dirty environments. The final piece of the solution is polycarbonate which is used to soak up the broken pieces of glass and prevent them from entering the vehicle. The solution must be installed on the vehicle in the correct orientation (strike face out), as much testing and research has shown that when the solution is installed incorrectly, the TA will suffer a major decrease in ballistic protection.

Temperature can also play a role in the effectiveness of the TA. Hot as well as cold testing must be performed to understand how the solutions work in all types of environments. During the summer, the elevated temperatures seen in Iraq and Afghanistan have been known to cause a decrease in ballistic protection. In addition, de-lamination of the glass and plastic layers has been observed at higher temperatures, resulting in lower visibility. Cold temperature testing reveals when vendors have used interlaminate adhesive materials that become brittle at low temperatures. Most vendors now use urethane which does not exhibit low temperature brittleness. Consequently, higher importance is placed on the elevated temperature protection as opposed to the cold temperature protection.

Although the ballistic protection of TA is essential, another important aspect of TA is optical clarity. Vehicles are far more difficult to drive and operate if a Soldier does not have clear visibility from the inside. Without clear visibility, the Soldiers will not be able to carry out their daily tasks, which may include spotting roadside mines and

locating insurgent hiding places. To ensure sufficient visibility, the TA solution must have adequate light transmission values at specified ranges in the visible and infrared light spectra. This is especially important for Soldiers who are using night vision goggles.

In the past, the Army has had the problem of TA vendors shipping "green" glass. Green glass is caused by a high concentration of iron which tints the glass a slight shade of green. This green glass is cheaper to process than clear white water glass because it is made with a greater number of impurities. Soldiers who have operated vehicles with green glass installed have reported low visibility in normal conditions, and almost no visibility when using night vision goggles. These complaints have caused the Army to reject green glass from vendors.

As mentioned earlier, U.S. Army vehicles face two main threats, armed insurgents and IEDs. The armed insurgents are usually equipped with handguns, small caliber rifles, or medium machine guns. This type of threat is known as small arms fire. These small arms threats come in all different sizes, ranging from a 9mm all the way up to a .50 caliber. The small arms projectiles can also vary, and include ball ammunition, armor piercing rounds (AP), and tracers. For the testing performed under the present study, the IED threat was simulated using a Fragment Simulating Projectile (FSP). The FSP is used to model the fragments generated by an exploding artillery shell.

Criteria and Parameter Restrictions

For evaluating the effectiveness and viability of our test procedure as a means of comparing and contrasting different TA solutions, three requirements have been outlined. This evaluation is based on the following criteria:

- The data that is obtained from testing must be accurate and repeatable.

- The data that is obtained must provide useful information allowing upper management to make informed decisions based on these results.

- Light transmission data must verify that the laminate recipe meets the minimum standard for use with night vision goggles.

Methodology

Published Army documents and direct observation of ballistic testing were used to justify the effectiveness of the test procedure.

Primary Purpose

The purpose of this thesis is to examine and validate the testing method used in ATPD 2352 as well as the light transmission requirements outlined in the specification.

Overview

The following chapters will discuss the results of the ballistic testing, followed by an explanation of the results attained. Analysis of both the testing method and the collected data will be included. Also incorporated are the results from light transmission testing, along with an explanation of these results.

II. BALLISTIC TESTING

The U.S. Army requires ballistic testing on all vehicles that see combat while in service. It is important for the engineers to design these vehicles to provide as much protection as possible while also keeping the weight of the vehicle to a minimum. In terms of protection, TA is one of the weakest areas on the vehicle and also the most inefficient when comparing weight versus ballistic protection. Since windows and windshields provide attackers with a line-of-sight on their target, they are some of the most heavily attacked areas on the vehicle. With this in mind, a complete understanding of how the TA will react under different threats is necessary.

Testing toward Specification

The U.S. Army is in the process of developing a new specification for testing TA. ATPD 2352, a TACOM purchase specification, is in development and close to being accepted as a standard Army specification. ATPD 2352 outlines all of the key requirements that a TA solution must possess to be considered for purchase by the Army. This specification places an emphasis on the ballistic performance, light transmissivity, and environmental durability of a TA solution. Exceptional results in these areas have proven to be essential in selecting superior TA solutions.

This new specification is required because current ballistic threats far exceed any of the requirements outlined in available specifications. The Army formerly used commercial specifications to purchase TA, however, with the development of this new

specification, the Army now has its own standard document for purchasing TA. There are many different commercial testing methods available for use; however, most of these only cover handguns and small caliber rifle rounds. U.S. Army vehicles face a larger range of heavier ammunition than accounted for by these commercial standards. Although the specific threats and the test results necessary to achieve acceptance are classified for ATPD 2352, Figure 2 illustrates the National Institute of Justice (NIJ) test standard which specifies the results required for commercially available TA.

Test Variables				Performance Requirements		
Armor Type	Test Ammunition	Nominal Bullet Mass	Suggested Barrel Length	Required Bullet Velocity	Required Hits Per Armor Specimen	Permitted Penetrations
I	22 LRHV Lead	2.6 g 40 gr	15 to 16.5 cm 6 to 6.5 in	320 ± 12 m/s 1050 ± 40 ft/s	5	0
	38 Special RN Lead	10.2 g 158 gr	15 to 16.5 cm 6 to 6.5 in	259 ± 15 m/s 850 ± 50 ft/s	5	0
II-A	357 Magnum JSP	10.2 g 158 gr	10 to 12 cm 4 to 4.75 in	381 ± 15 m/s 1250 ± 50 ft/s	5	0
	9 mm FMJ	8.0 g 124 gr	10 to 12 cm 4 to 4.75 in	332 ± 12 m/s 1090 ± 40 ft/s	5	0
II	357 Magnum JSP	10.2 g 158 gr	15 to 16.5 cm 6 to 6.5 in	425 ± 15 m/s 1395 ± 50 ft/s	5	0
	9 mm FMJ	8.0 g 124 gr	10 to 12 cm 4 to 4.75 in	358 ± 12 m/s 1175 ± 40 ft/s	5	0
III-A	44 Magnum Lead SWC Gas Checked	15.55 g 240 gr	14 to 16 cm 5.5 to 6.25 in	426 ± 15 m/s 1400 ± 50 ft/s	5	0
	9 mm FMJ	8.0 g 124 gr	24 to 26 cm 9.5 to 10.25 in	426 ± 15 m/s 1400 ± 50 ft/s	5	0
III	7.62 mm 308 Winchester FMJ	9.7 g 150 gr	56 cm 22 in	838 ± 15 m/s 2750 ± 50 ft/s	5	0
IV	30-06 AP	10.8 g 166 gr	56 cm 22 in	868 ± 15 m/s 2850 ± 50 ft/s	1	0
Special Requirement (see sec. 2.2.7)*	*	*	*	*	*	*

* These items must be specified by the user. All of the items must be specified.

Abbreviations: AP - Armor Piercing
FMJ - Full Metal Jacket
JSP - Jacketed Soft Point
LRHV - Long Rifle High Velocity
RN - Round Nose
SWC - Semi-Wadcutter

Figure 2. Ballistic performance requirements. NIJ, September 1985. Ballistic Resistant Protective Materials. NIJ Standard 0108.01.

ATPD 2352 also includes requirements for FSP testing. The FSP threat is military specific and is not outlined in any commercial specification. FSP testing has recently become a priority for the Army since IED related vehicle deaths have been on the rise. With the inclusion of FSP testing on ATPD 2352, the Army now has a sufficient test method to test TA against this threat.

Test Set-up

Ballistic testing was done at the TARDEC Armor Integration Laboratory (TAIL) located on base in Warren, MI. This facility houses an indoor testing range as well as a drop tower that is used for landmine blast simulation. During testing, the projectiles are fired from one end of the range into the impact chamber where the samples are set up. Inside the impact chamber the test fixture supports the sample that is being tested. Between both ends of the range is a chronograph, which is used to determine the velocity of the fired projectile. Figure 3 illustrates this set-up.
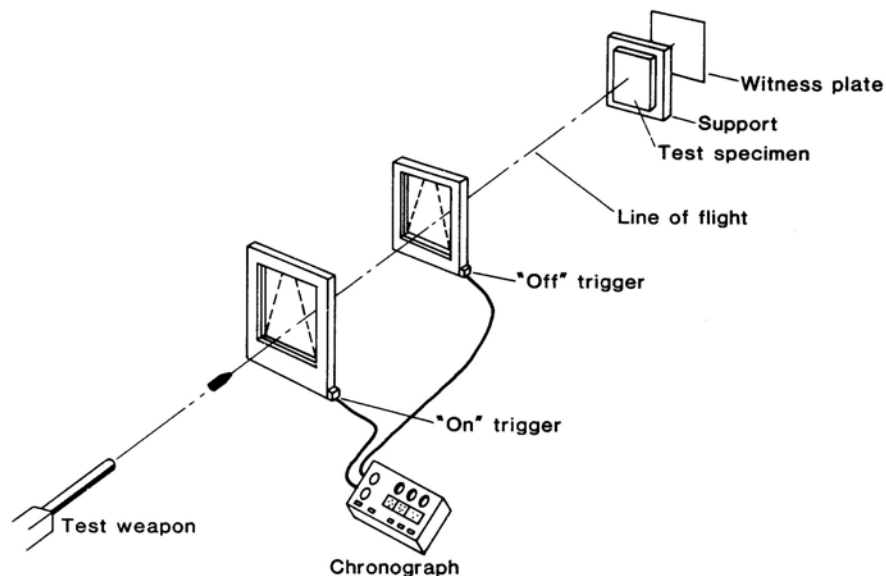

Figure 3. Sample test set-up. NIJ, September 1985. Ballistic Resistant Protective Materials. NIJ Standard 0108.01.

To support the glass samples evaluated in this study properly, a new test fixture was specifically fabricated. The new test fixture helped ensure a consistent and repeatable setup between all vendors and samples tested. A piece of aluminum foil behind the test setup was used as a witness plate. The witness plate, in the case of opaque armor, simulates a Soldier's skin and uniform. In the case of TA, the witness plate is thinner, and simulates a Soldier's eyes. A perforation in the witness plate indicates that a Soldier not wearing eye protection will suffer an injury. If this result should occur, the test is marked as a complete penetration and the sample is considered a failure. The distinction between a complete and partial penetration is shown in Figure 4.
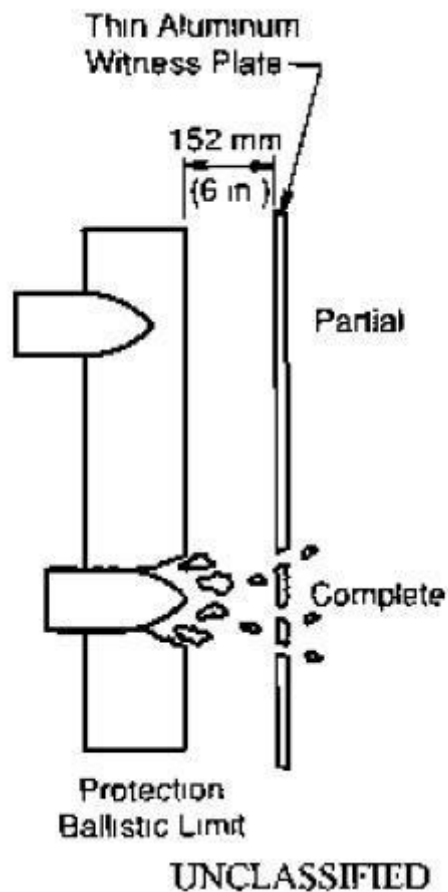

Figure 4. Example of partial and complete penetrations.

Testing

Glass samples were ordered from four different TA suppliers. Sixteen pieces were ordered from each supplier except for one. In that case, thirty-two samples were ordered for the purpose of conducting elevated temperature testing. All of the samples ordered were 12"x12" and had a nominal thickness of 73mm (≈ 2.9").

The orientation of testing was originally specified as a single 20mm FSP shot aimed at the center of the TA sample. Testing two panels in this manner indicated that this test method was not going to provide results that were accurate or usable. This is because the 20mm FSP threat was an overmatch for the size of test sample used. Simply put, there was not enough material in the sample to absorb all of the energy that was generated by the FSP. Previous testing of samples with the same thickness, but with a surface area 1.7 times larger than 12"x12", showed that the 20mm FSP threat can be stopped at the test velocity. This finding indicates the possibility that data and results from windshield tests can no longer be compared equally to side window tests, since side windows are usually much smaller and are therefore unable to absorb the same amount of energy. Furthermore, results from sample testing cannot be accurately compared unless the samples have the same surface area and overall dimensions. ATPD 2352 requires a uniform sample size for all testing, to eliminate the advantages, or disadvantages, of different sample sizes.

Since the 20mm FSP threat was an obvious overmatch for our solutions, the focus of the testing switched from a single FSP shot to a multi-hit rifle pattern. The projectile chosen for testing was the .30 caliber M2AP round and the test pattern used is documented in ATPD 2352. The test pattern, which is unique to ATPD 2352, was

developed with the help of a TARDEC research project used to write a NATO Test

Standard (STANAG).   Figure 5 illustrates the test pattern used for testing.
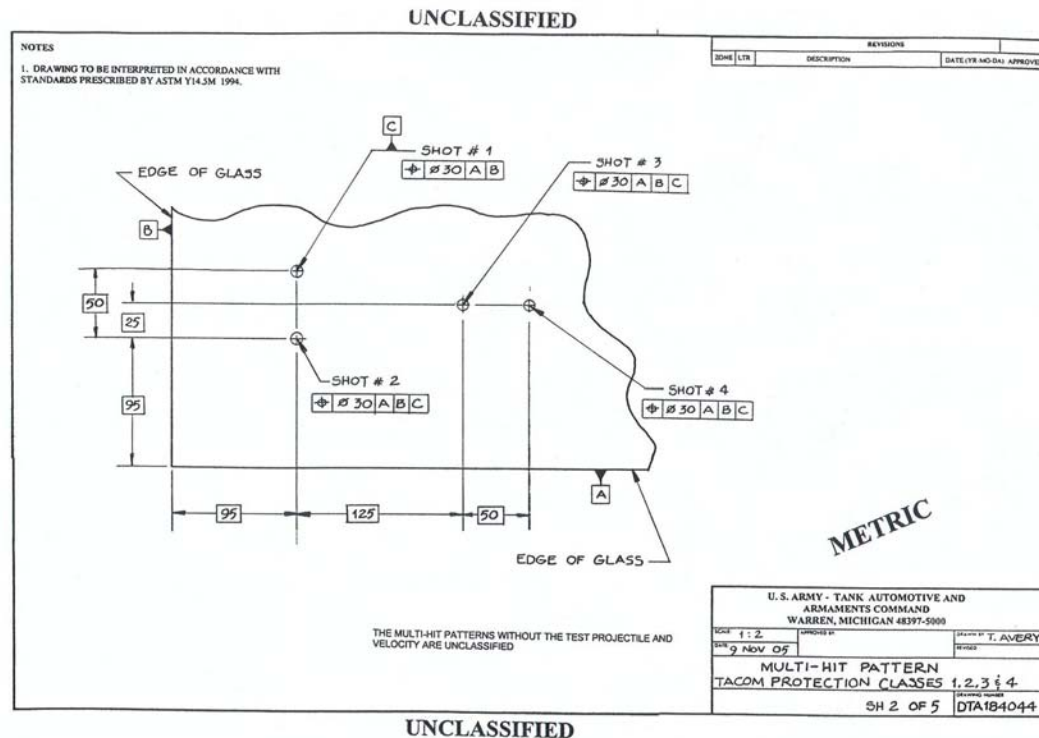
Figure 5. Multi-hit test pattern (units in mm)

With this method of testing TA, the engineer seeks to identify the velocity of the

chosen threat at which there is only a five percent chance of penetrating the solution.

This is different from testing opaque armor, where the engineer is testing to find the

velocity at which fifty percent of the projectiles will penetrate the armor, this is known as

a V_{50}. The V_{50} method is outlined in the military document MIL-HDBK-690(AT).

> Another ballistic limit test, known as the six-round limit, uses three
> complete penetrations and three partial penetrations within a specified
> velocity range – usually 27, 38, or 46 m/s (90, 125, 150 ft/s). Firing is
> discontinued as soon as three complete penetrations and three partial
> penetrations are obtained within the specified velocity range. The striking

velocities of the three lowest complete penetrations and the three highest partial penetrations are averaged to obtain the V_{50} ballistic limit. The six-round ballistic limit is reasonably accurate and generally is used to test metallics and nonmetallics, regardless of the size of the projectiles.

A V_{50} is often used for opaque armor testing as a quick method to acquire data on how effective the armor is. A V_{50} value also gives the designer a result that is representative of the solution at its breaking point. During V_{50} testing, each shot is counted as a different statistical event. Individual shots are physically spaced far enough apart so that each new shot is considered to be taken on virgin material. This is opposed to a multi-hit pattern, where the panel is conditioned by previous shots, making some shots more difficult to pass than others. In the ATPD 2352 pattern, all fours shots on the target are considered one statistical event, not each individual shot. The following is an equation for finding the V_{50} of a sample.

$$V_{50} = \frac{S_V}{N_P + N_C} \tag{1}$$

S_V = sum of the striking velocities of all rounds in the zone of mixed results, m/s (ft/s)

N_P = number of partial penetrations in the zone of mixed results, dimensionless

N_C = number of complete penetrations in the zone of mixed results, dimensionless

The data analysis method used for the TA tests is known as a logistic response function. In this case, this testing method gives the probability of penetration in relation to the velocity of the projectiles. Since the results are given as a probability, all values stay between the boundaries zero and one. While testing, a partial penetration is reported as a zero and a complete penetration is reported as a one. There are two reasons why this

type of data analysis is used for TA testing. First, a logistic regression curve determines the relationship between velocity and penetration, and second, the curve provides for an estimation of the velocity needed to produce a certain level of penetrations. The logistic regression model can be written as

$$\text{Probability of Penetration} = \frac{1}{1 + e^{-(\beta_0 + \beta_1 \bullet velocity)}} \tag{2}$$

where β_0 and β_1 are coefficients estimated from the data. Since the logistic function to be fitted is nonlinear, a transformation is chosen to make the response function linear. The weighted least squares are typically used to estimate the values of β_0 and β_1.

There are a few problems with this type of data analysis. First, a relatively large number of data points are required for the testing. Compared to the six to ten data points needed for a V_{50}, the logistic response function needs more data to generate an accurate curve throughout the entire range of velocities. The second problem comes when the testing is completed and there is no zone of mixed results. When the logistic regression curve of this data is plotted, the resulting curve looks similar to a step function, as seen in Figure 6.
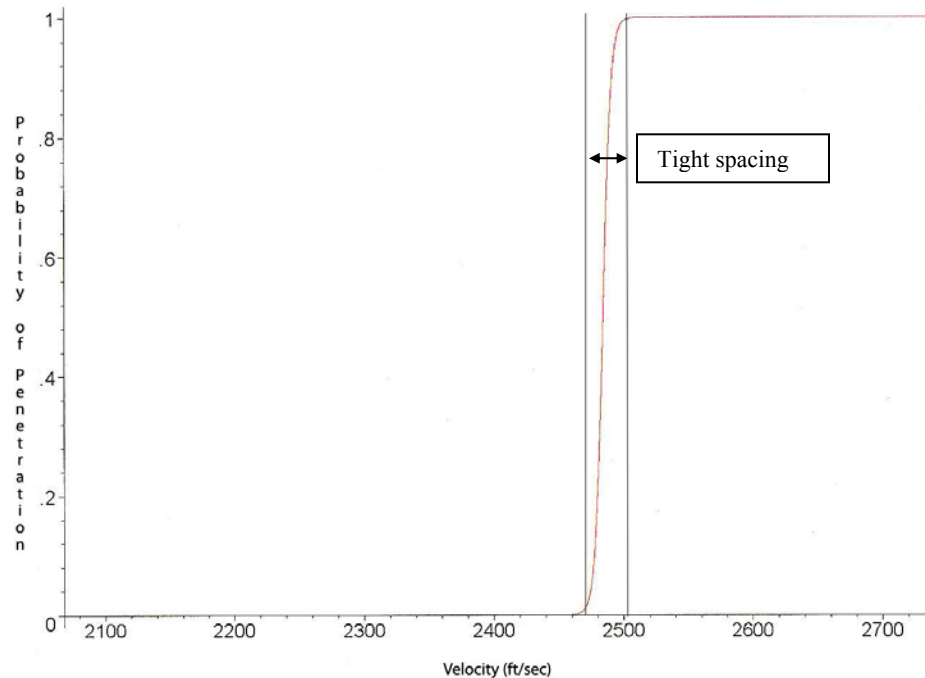
Figure 6. Example of step function curve.

Figure 6 shows that the solution has a very tight spread between a pass and a fail, which is seldom observed in real-world use. However, testing more samples and attaining a zone of mixed results may remedy this problem.

Figure 7 shows that achieving a zone of mixed results will give a much larger spread between pass and fail. A zone of mixed results occurs when a sample passes (i.e., only partial penetrations) at a higher velocity than another sample that fails (i.e., a complete penetration occurs). Third, this type of data analysis relies heavily on statistics. Those who do not have a general knowledge of statistics may have a more difficult time interpreting and understanding the results as opposed to V_{50} results, which are generated simply by averaging six numbers together.
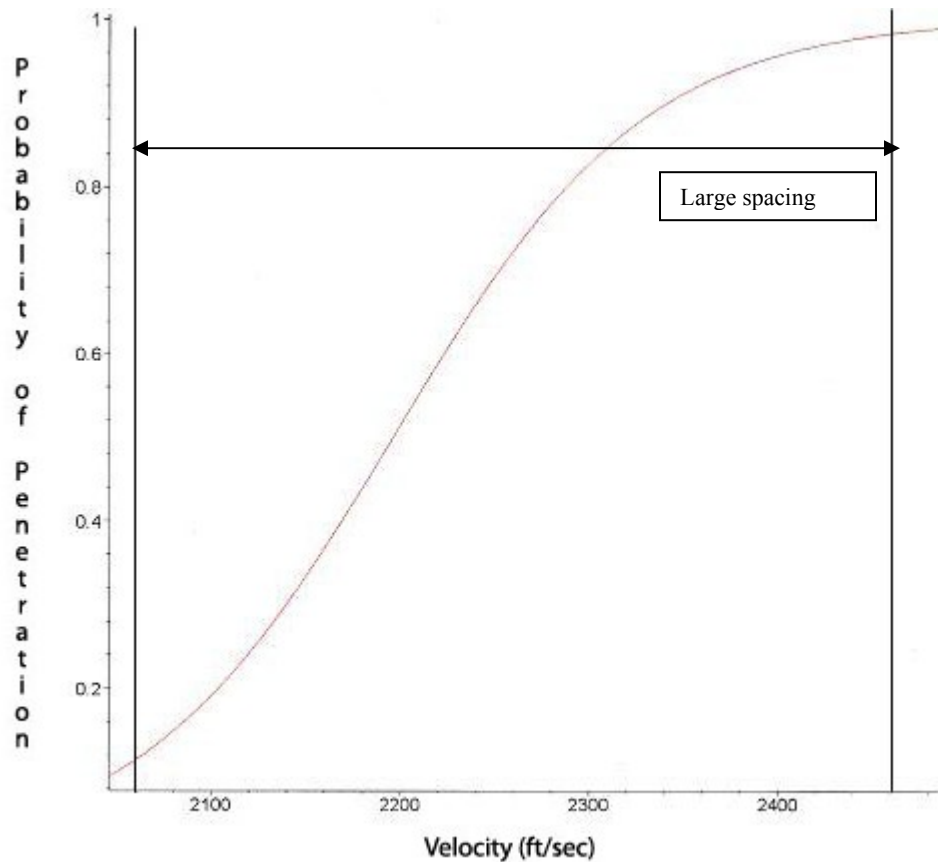
Figure 7. Example of logistic curve with zone of mixed results.

Results

The testing was conducted over a four-week period. During this period, the samples were shot and the data was collected and analyzed on a daily basis. Each sample was subjected to the pattern of four shots, and testing was stopped at the first complete penetration. After each shot, the samples were photographed and then checked for a partial or complete penetration. Based on previous knowledge and test experience, it was known that complete penetrations were more likely to occur during either the second or fourth shot, since each of these shots was the second projectile placed in a tight area. All of the shots taken on each individual sample were similar in velocity, so if 2200 ft/sec

was the target velocity of the projectile for a given sample, then each shot on the sample

was 2200 ±50 ft/sec. The velocity listed in the tables is simply the average velocity of all

the shots taken on that sample.

The vendors were kept anonymous for the disclosure of the results. They are

labeled as vendor A, B, C, or D. The results for each vendor can be found below in

Tables 1 through 4.

Table 1

Vendor A Results

Vendor A		
Sample #	Avg. Velocity (ft/s)	Penetration Type
1	2068	Partial
2	2099	Partial
3	2175	Partial
4	2204	Partial
5	2347	Partial
6	2427	Partial
7	2537	Complete
8	2539	Complete
9	2607	Complete
10	2741	Complete

Table 2

<u>Vendor B Results</u>

Vendor B		
Sample #	Avg. Velocity (ft/s)	Penetration Type
1	2044	Partial
2	2160	Partial
3	2243	Partial
4	2262	Partial
5	2273	Complete
6	2281	Complete
7	2287	Complete
8	2292	Complete
9	2350	Complete
10	2353	Complete
11	2435	Complete
12	2544	Complete
13	2582	Complete
14	2712	Complete

Table 3

<u>Vendor C Results</u>

Vendor C		
Sample #	Avg. Velocity (ft/s)	Penetration Type
1	2223	Complete
2	2224	Complete
3	2235	Partial
4	2261	Complete
5	2278	Complete
6	2290	Partial
7	2372	Complete
8	2413	Complete
9	2486	Complete

Table 4

Vendor D Results

Vendor D		
Sample #	Avg. Velocity (ft/s)	Penetration Type
1	1776	Partial
2	1920	Partial
3	2046	Partial
4	2194	Complete
5	2338	Partial
6	2412	Complete
7	2421	Complete
8	2444	Partial
9	2542	Complete
10	2575	Complete
11	2678	Complete

The number of samples tested was determined by the number of samples available

for testing. Vendors A and B could not achieve a zone of mixed results with the number

of samples tested. The logistic regression curves for these results resemble a step

function, previously shown in Figure 6. It is unclear whether the sample truly behaves in

this way, or if further testing of these samples would reveal a zone of mixed results.

Samples from vendors C and D were able to achieve a zone of mixed results, giving

regression curves that are similar to expected and shown in Figure 7. Further testing of

these samples would allow for the curve to become more representative of the actual

performance. Appendix C contains a graphical representation of the results.

The curve for vendor A is located at a higher velocity than the curves for vendors

B, C, and D. Further testing and data analysis should reveal if vendor A is truly a better

solution. As mentioned earlier, the curves for vendors C and D seem to be more representative of a logistic response curve than the curves generated by vendors A and B. Currently, it is uncertain if this indicates statistically superior results, or if the samples for vendors A and B truly behave in this manner.

III. LIGHT TRANSMISSION TESTING

Light transmission testing is necessary on all of the different solutions of TA. The TA solution must have a certain level of light transmission through a selected range of the visible light spectrum in order to be functional. If the operator's vision through the TA becomes inadequate, the operator will no longer able to perform their duties to their full potential. The driver may have a difficult time seeing the road and the other occupants may not be able to detect threats to the vehicle such as roadside IEDs. This type of testing becomes more important as the TA solutions become thicker since there is more material to look through and there is a higher probability of finding defects in the solution. Previous research indicated that lower light transmission levels occur when the solution contains "green" glass, or if the solution includes a large amount of plastic.

Requirements

The requirements for light transmission testing outlined in ATPD 2352 are as follows:

> The integrated luminous (photopic) transmittance of transparent armor shall be equal to or greater than 70% for protection classes 1 through 3, TBD for protection class 4, and TBD for protection class 5, measured according to the photopic transmission measurement procedure given in MIL-DTL-62420. For compatibility with night vision goggles the spectral transmission shall not be less than 50% at all wavelengths from 550 nm to 1000 nm, and shall be not less than 72% at 550 nm when tested using a spectroradiometer.

This means that protection classes 1 through 3 must have at least a 70 percent average

photopic transmission, or the TA fails. Also, the occupants must have at least 50 percent

photopic transmission while wearing the PVS14 Gen III Night Vision Goggles. Photopic

transmission is a weighted value that is calculated based on the light transmission of the

sample, the human eye photopic response curve, and a "weighting" for the artificial light

source. The visible light photopic transmission is derived from:

$$X = \sum_{400}^{700} T(w)S(w)V(w)dw \tag{3}$$

$$Y = \sum_{400}^{700} S(w)V(w)dw \tag{4}$$

$$PT = X\!\!\Big/\!\!Y \tag{5}$$

w = Wavelength
$T(w)$ = Sample Measured Light Transmission
$S(w)$ = Artificial Light "weighting"
$V(w)$ = Eye Photopic Response
dw = 10 nm Intervals

Test Method

Testing was done using a Perkin Elmer 900 Lambda Series Spectrophotometer.

The sample light transmission was tested through the visible light spectrum, from 400nm

to 1000nm wavelengths. The results were then calculated and compared to one another,

as well as the specification requirements.

Results

The results of the photopic transmission can be seen below in Table 5.

Table 5

Photopic Transmission Results

Photopic Transmission	
Vendor	PT (%)
A	72.2
B	59.5
C	82.5
D	62.5

The photopic transmission results came out as expected. Both of the samples of "green" glass failed the photopic transmission testing according to the guidelines set in ATPD 2352, while both of the clear glass solutions passed. The value that is given in Table 5 is an average transmission percentage over the wavelength range extending from 400nm to 700nm. For a graph of the transmission percentage over the entire range of wavelengths, please refer to Appendix D.

The results for the PVS14 Gen III transmission can be seen in Table 6.

Table 6

Night Vision Transmission Results

Night Vision Transmission	
Vendor	PT (%)
A	63.8
B	25.7
C	76.5
D	28.3

Again, these results clearly show that the "green" glass failed the night vision transmission testing. Although the average photopic transmission for Vendor A was

above 60 percent, it still failed the night vision goggle testing because transmission

dropped below the 50 percent minimum at the 920nm wavelength range.

IV. CONCLUSIONS AND RECOMMEDATIONS

The U.S. Army is continually searching to improve vehicle occupant protection. As new technologies become available, they must be tested and compared to existing technologies to observe any discernable difference, either good or bad. It is the job of the test engineer to derive the most effective means of testing to efficiently and accurately compare two different samples of transparent armor.

Conclusions

Based on the results of the ballistic testing, two conclusions could be drawn from the data gathered.

1. Ballistic testing results are dependant upon the overall physical size of the sample being tested. A uniform test sample size must be specified in order to directly compare different TA solutions.

2. No zone of mixed results in the data means the probability of penetration curve will have a very tight spacing between pass and fail. Acquiring a zone of mixed results extends the probability of penetration curve over a much larger velocity range.

Recommendations

1. Further testing is suggested to confirm the repeatability of the results.

2. Research is recommended to determine the ideal physical size for test samples.

3. Further testing is recommended to determine if the probability of penetration curve with a very steep slope, is an accurate representation of the actual performance of the TA solution.

4. Determine if data is accurate when the pattern is broken down into two, two shot patterns when compared with one, four shot pattern.

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Ballistic Resistant Protective Materials. NIJ Standard 0108.01. National Institute of Justice, U.S. Department of Justice, Washington DC 20531

MIL-HDBK-690(AT)

Purchase Specification Transparent Armor. ATPD-2352.

ACRONYMS

AP	Armor Piercing
ATPD	Transparent Armor Purchase Document
FSP	Fragment Simulating Projectile
IED	Improvised Explosive Device
TA	Transparent Armor
TACOM	Tank-Automotive Command
TAIL	TARDEC Armor Integration Laboratory
TARDEC	Tank-Automotive Research Development and Engineering Center

APPENDICES

APPENDIX A

PICTURES OF TEST SET-UP

This appendix gives an overall view of the test set-up, as well as pictures of the individual components.

Figure A1. Metal test fixture with witness plate mounted behind.

Figure A2. Wooden frame constructed for TA solutions.

Figure A3. TA solution mounted in wooden frame and attached to metal frame.

Figure A4. Overall view of test set-up.

APPENDIX B

TEST SAMPLE PICTURES

This appendix contains pictures from the ballistic testing, including both 20mm and the multi-hit rifle pattern.

Figure B1. Rear view of TA sample tested with 20mm FSP.

Figure B2. Piece of TA solution on floor after 20mm FSP shot.

Figure B3. Front view of TA solution tested with 20mm FSP.

Figure B4. Front view of TA sample after 4 rifle shots in multi-hit pattern.

APPENDIX C

BALLISTIC TESTING RESULTS

This appendix gives the graphical results of the ballistic test results from each vendor. These graphs represent probability of penetration vs. velocity.
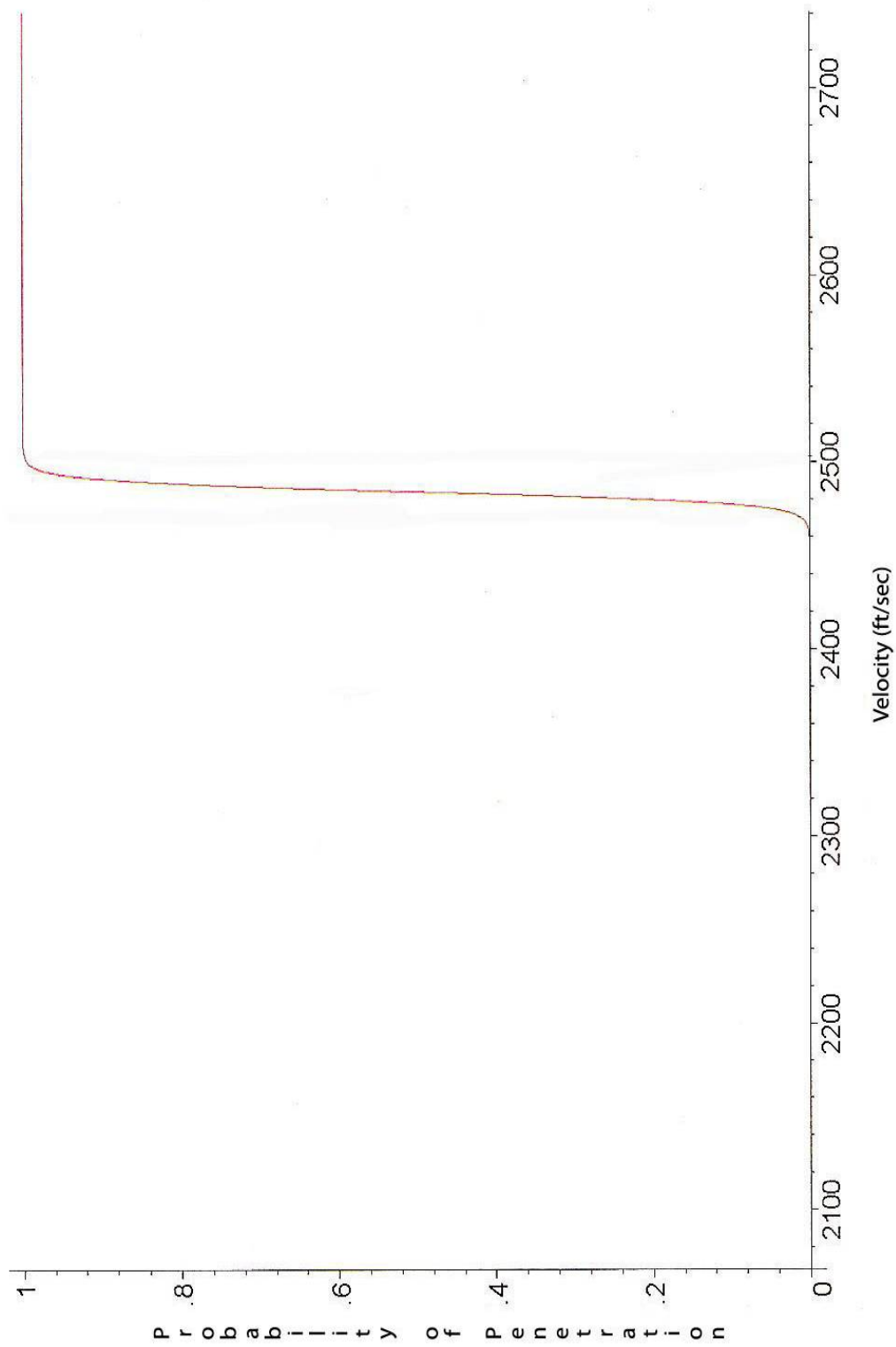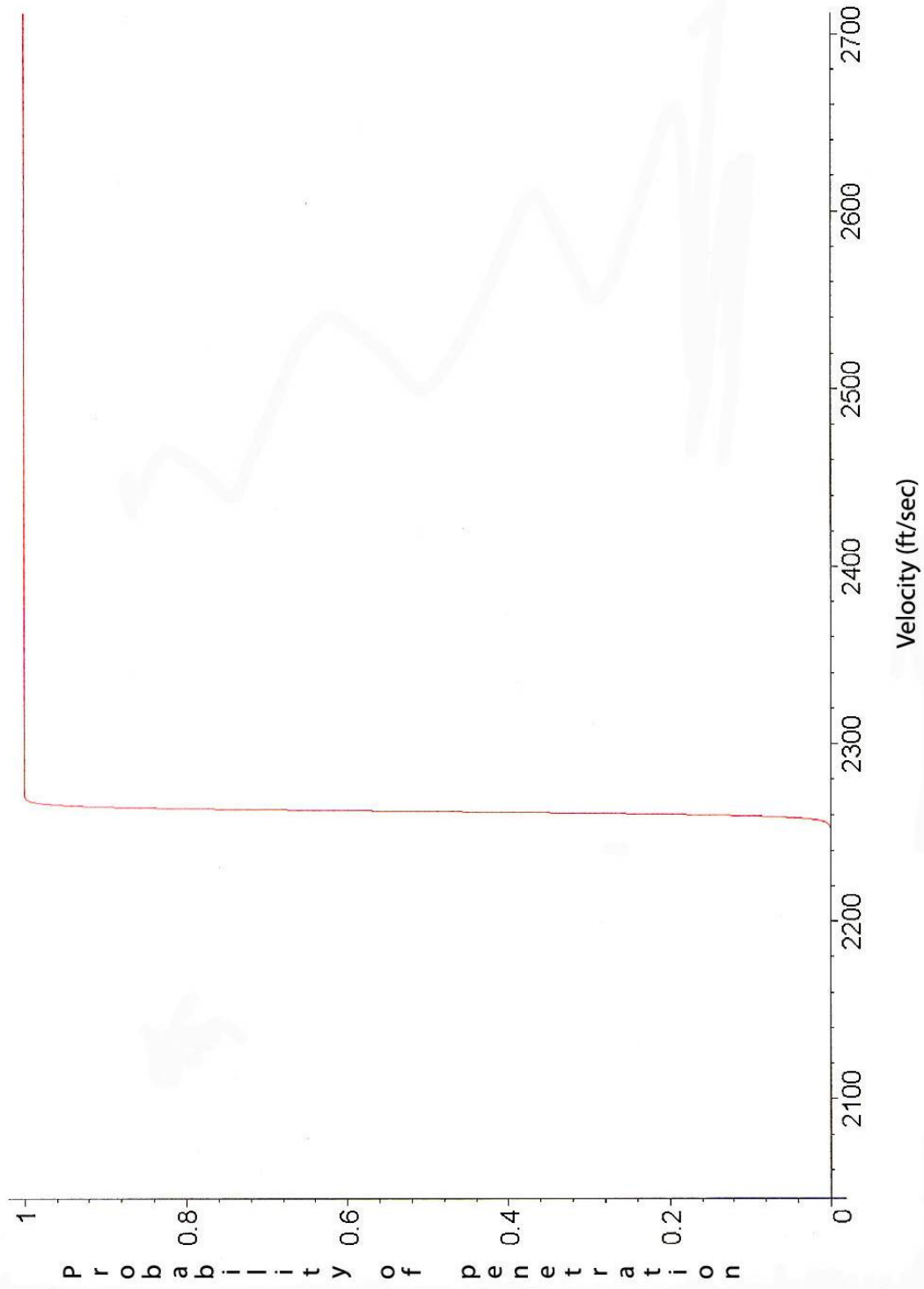
Figure C1. Results from Vendor A.
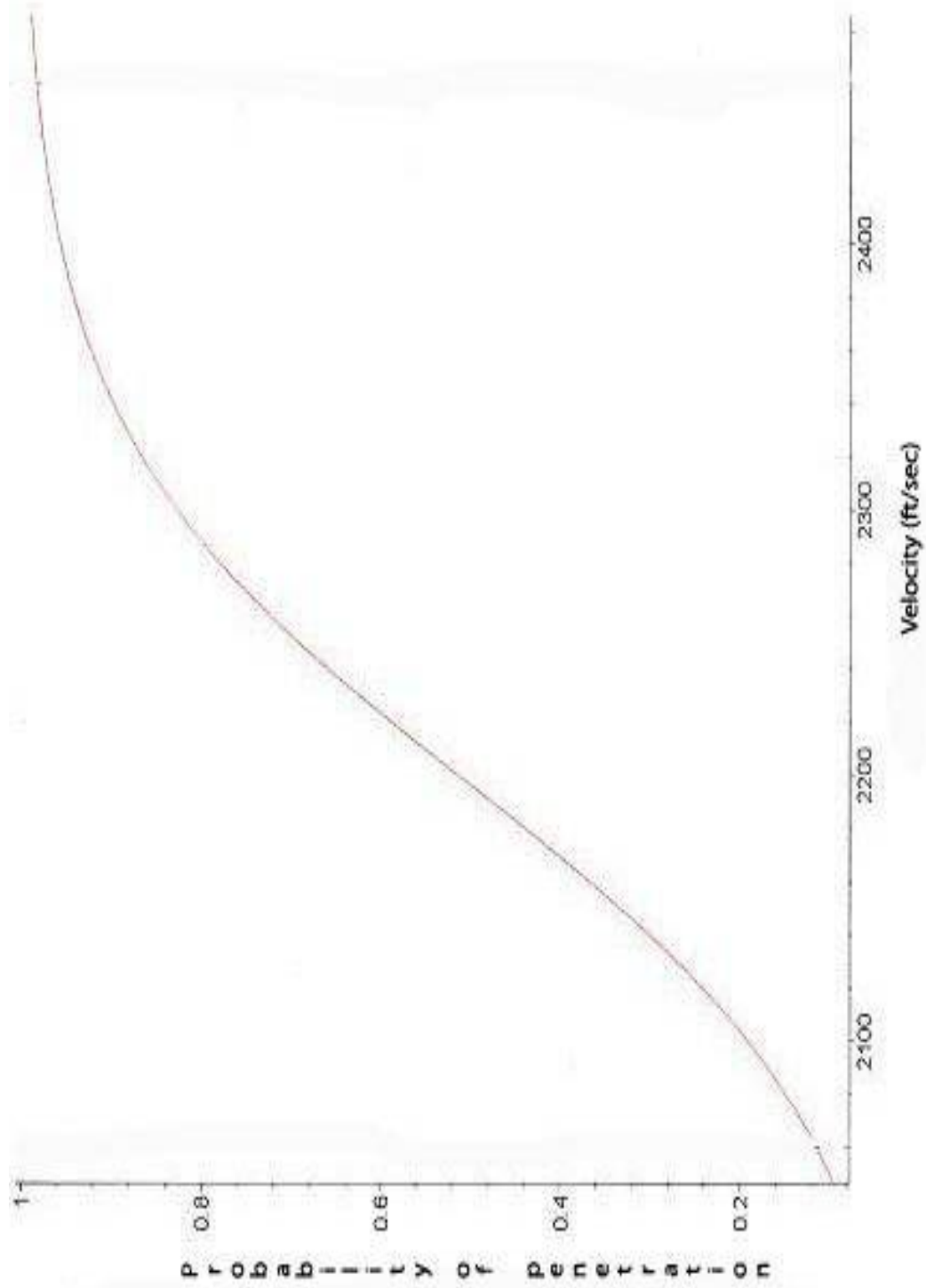
39

Figure C2. Results from Vendor B.

40

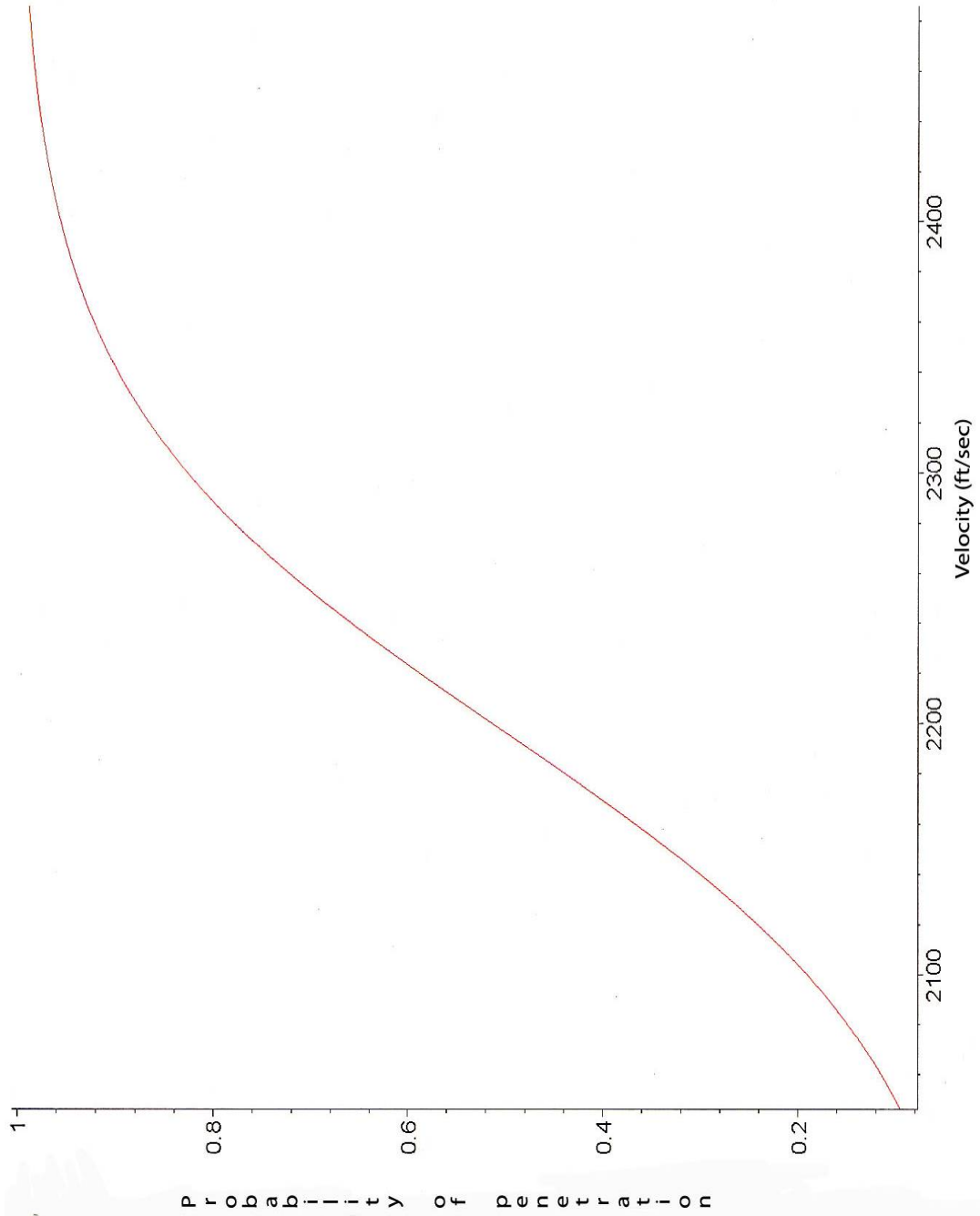Figure C3. Results from Vendor C.

41

Figure C4. Results from Vendor D.

APPENDIX D

LIGHT TRANSMISSION RESULTS

This appendix gives the results of the entire range of light transmission testing in graphical form.
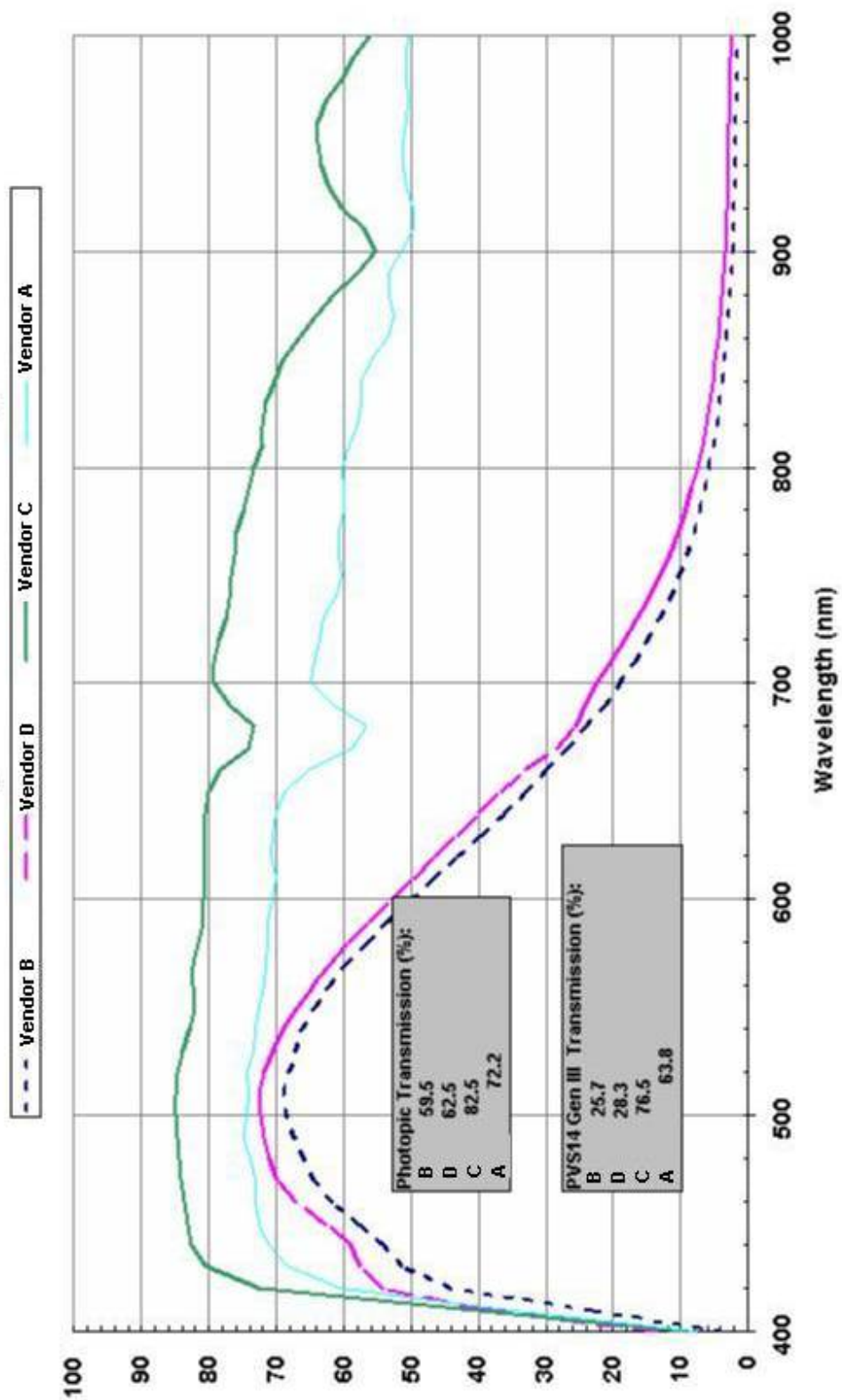
Figure D1. Light Transmission Test Results

APPENDIX E

ABET PROGRAM OUTCOMES

A. An ability to apply knowledge of mathematics, science, and engineering.

   This investigation required the ability to apply the knowledge of mathematics, science, and engineering to analyze the accuracy and effectiveness of the testing method outlined in ATPD 2352.

B. An ability to design and conduct experiments, as well as to analyze and interpret data.

   The program outcome was an analysis of the data collected and was used to measure the effectiveness of the testing method and the repeatability of the data.

C. An ability to design a system, component, or process to meet desired needs.

   This program outcome was utilized in the fabrication of the test fixtures needed to complete the testing.

D. An ability to function on multi-disciplinary teams.

   This program outcome was shown in that the student was required to work with mechanical and optical engineers and statisticians to complete this thesis.

E. An ability to identify, formulate, and solve engineering problems.

   This skill was required to compare the results of each vendor as well as analyze the data that was collected.

F. An understanding of professional and ethical responsibility.

   Due to the nature of the testing performed, professional and ethical responsibility was necessary. It is important that the testing and results are accurate in to ensure the safety of United States Soldiers.

G. An ability to communicate effectively.

   This thesis, as well as the necessity to communicate with statisticians' shows that the student has an ability to communicate effectively.

H. The broad education necessary to understand the impact of engineering solutions in a global and societal context.

Ballistic testing and armored vehicle safety are especially important now as United States troops are fighting in Iraq and Afghanistan. Casualties of any sort reduce morale, and erode public confidence and support in a war or peacekeeping military effort. By decreasing the number of casualties, society may be more supportive of military operations.

I. A recognition of the need for, and an ability to engage in lifelong learning.

Further learning will be required to improve the test procedure and test method. The ballistic requirements are always changing in this environment so constant learning is necessary to keep up-to-date on current situations.

J. A knowledge of contemporary issues.

The student recognizes that there is conflict and fighting taking place all over the world. When United States Soldiers are involved in these conflicts it is important that they are well protected and as safe as possible.

K. An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

The student was required to use computer based analytical software to analyze the data collected during testing.

L. An ability to work professionally in both thermal and mechanical systems areas including the design and realization of such systems.

The student was not required to complete this task for this thesis project.

M. A competence in the use of computational mathematics tools and systems analysis tools germane to the world of engineering.

The student used Maple in order to determine the probability of penetration at selected velocities.

N. A competence in experimental design, automatic data acquisition, data analysis, data reduction, and data presentation, both orally and in the written form.

The student was required to verify the accuracy of the current testing method and statistically analyze the results acquired. The data has been presented to the employer in written form and will be published for future Army use.

O. A competence in the use of computer graphics for design communication and visualization.

The student was not required to complete this task for this thesis project.

P. A knowledge of chemistry and calculus based physics with a depth in at least one of them.

A knowledge of chemistry was not required for the completion of this thesis project. A knowledge of physics was required to understand the effects of the transparent armor when struck by the projectile. It is important to understand how the material reacts to large forces.

Q. An ability to manage engineering projects including the analysis of economic factors and their impact on the design.

The experiment designed took economic factors into account in the selection of transparent armor for testing. The sample size required for testing was chosen to give accurate results while maintaining a low price.

R. An ability to understand the dynamics of people both in a singular and group setting.

This thesis required the student to work with engineers and management from TARDEC as well as the suppliers in both singular and group settings.

S. A competence in the analysis of inter-disciplinary mechanical/electrical/hydraulic systems.

The student was not required to complete this task for this thesis project.